Benchmark Tests for Fragmentation and Propagation Models

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Abstract

The FRAGPROP model predicts probabilities of propagation of detonation and burning between ammunition stacks. In order to benchmark predictions from FRAGPROP, propagation tests using 155-mm M107 ammunition were conducted. The predicted frequencies of detonation and burning propagation are somewhat greater than those observed in the tests. While the results do not provide sufficient data to validate the FRAGPROP predictions with a high level of confidence, they indicate that they are reasonable representations of the actual responses of these munitions. FRAGGEN is a simple model for estimating the fragment output. In order to benchmark its predictions of fragmentation from a missile warhead, an arena test on a single Hellfire missile was performed. Analysis indicates that the predicted distribution is accurate for the smallest fragments. Measured fragment velocities were much lower than the Gurney predictions employed by FRAGGEN. Because the configuration used in the single Hellfire test does not represent the actual storage arrangement, an arena test on two Hellfire missiles in their containers was conducted. Comparison of the fragment mass distributions produced in the two tests indicates depopulation of the smaller fragment sizes in the second test. This renders the FRAGGEN predictions inaccurate. A final arena test with two 155-mm M864 ICM projectiles containing submunitions, conducted in an attempt to develop fragmentation data for this configuration, was not successful.

Background

The MUNITIONS SURVIVABILITY TECHNOLOGY program was initiated by the Army's Defense Ammunition Logistics Activity in order to develop a rapidly deployable system of fragment barricades combined with lightweight fire-inhibiting blankets along with guidelines for their use to prevent propagation of explosions and fire between stacks of Army munitions. One of the program's objectives is to enhance predictive techniques for propagation of detonation and burning between ammunition stacks. The primary predictive tool available is the FRAGPROP model developed at the U.S. Army Research Laboratory. FRAGPROP predicts probabilities of propagation between ammunition stacks by means of fragmentation. In order to represent a source or donor stack, the model requires arena test data characterizing the fragment output from the ammunition item comprising the stack. To account for effects of interactions between fragments from nearly simultaneously detonating adjacent munitions, more than one item must be included in the arena test source. In general, such data are only available for some of the munitions that derive their effectiveness from fragmentation. Items such as shaped-charge missile warheads and detonable rocket motors, which may also produce hazardous fragments, have not been experimentally characterized, and an adjunct model called FRAGGEN was developed to estimate their primary

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 1998**	2. REPORT TYPE	3. DATES COVERED **00-00-1998 to 00-00-1998**

4. TITLE AND SUBTITLE
Benchmark Tests for Fragmentation and Propagation Models

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory,Aberdeen Proving Ground,MD,21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001002. Proceedings of the Twenty-Eighth DoD Explosives Safety Seminar Held in Orlando, FL on 18-20 August 1998.

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**15**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

fragment output. In order to increase confidence in the predictions from these models, benchmark experiments for propagation and fragment output (arena tests) were conducted. Additionally, although data characterizing fragment output from submunitions may exist, no data or predictive techniques are available to characterize fragments produced when these are detonated en masse in their carriers. Tests were also conducted in an attempt to provide this information.

Brief Review of FRAGPROP

FRAGPROP (Starkenberg, Dorsey, and Frey 1996) is based on an earlier computer program called FRAGHAZ (McClesky 1988) that was developed to predict the hazard to a human target due to fragmentation from an exploding ammunition stack. FRAGPROP is designed to predict probabilities of detonation and burning propagation between two ammunition stacks as functions of the distance between them. The donor stack description and Monte-Carlo analysis of the trajectories of the fragments characterizing that stack are nearly identical to those used in FRAGHAZ. Effects of penetrating external containers and user-specified limits on fragment mass and initial elevation angle were added. FRAGPROP includes descriptions of the vulnerable components (warheads and rocket motors) of munitions in the acceptor stack and applies detonation initiation and burning ignition criteria whenever a fragment impacts the target stack. The effects of penetrating external containers are included here also. The vulnerability of a weapon component to initiation of detonation by fragment impact is described by the Jacobs-Roslund formula for critical impact velocity (Liddiard and Roslund 1993). The model for ignition of burning makes use of a threshold corresponding to a specified residual velocity computed using the THOR equations. The burning produced may be either mild or violent. The violence of the burning response is not predicted by FRAGPROP. Analysis has shown that a residual velocity of zero can be used as a worst-case without inordinately increasing the distance associated with a given probability.

Fragment Propagation Tests

Choice of Ammunition. The objective of the fragment propagation tests was to determine the frequency with which a well-characterized detonated donor stack produces detonation in nearby well-characterized acceptor stacks for comparison with FRAGPROP predictions. Since applicable fragmentation data for 155-mm M107 projectiles filled with Composition-B Jacobs-Roslund constants for initiating Composition-B, and THOR equation constants for penetration of mild steel are all available, propagation tests with pallets of M107s were conducted. Each M107 projectile contains 15.4 lb of Composition-B and is classified 1.1D for storage and shipping. Hawthorne Army Ammunition Plant, Nevada supplied 144 projectiles for three tests.

Test Arrangement. Three tests were conducted at the Naval Air Warfare Center, China Lake, in the center of a flat, dry lakebed approximately one-half mile wide. A schematic of the test arrangement is shown in Figure 1. In each test, the donor was configured by placing two eight-projectile pallets of M107s side by side, producing a stack having four projectiles on each of its four faces (identified as north, east, south, and west). A photograph of the donor pallets is shown in Figure 2. Acceptor stacks consisting of single pallets of M107s were placed opposite each of the

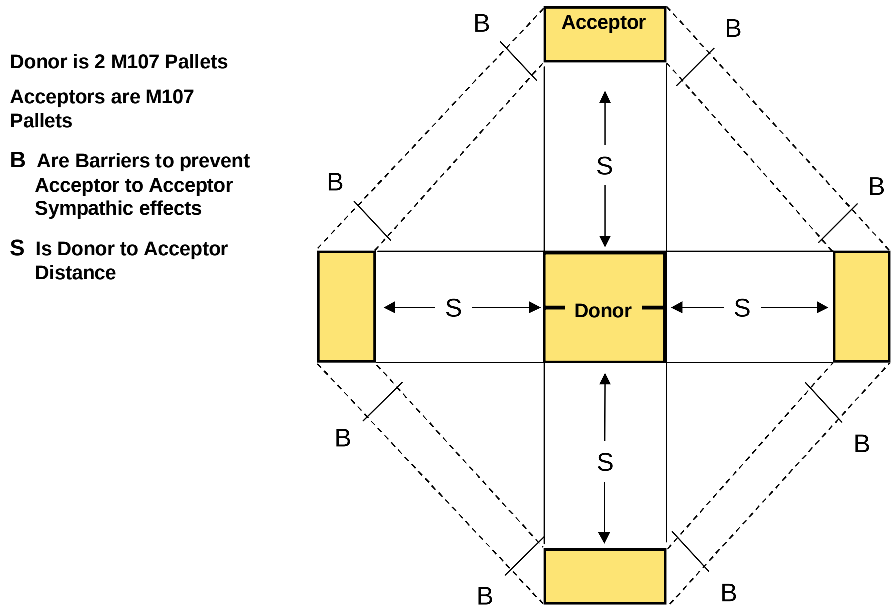


Figure 1. Schematic of Fragmentation Propagation Test Arrangement.

Figure 2. Donor Consisting of Two M107 Pallets.

donor faces at distances determined with reference to results of a FRAGPROP analysis. The distance between projectiles in the stacks was approximately 7/8 in. The four center projectiles in the donor pallets were each boosted with approximately 1.7 oz of Composition-C4, and each booster was primed with 24 in of 50-gr/ft detonating cord. The detonating-cord connections were cut to the same length to ensure simultaneous initiation of the projectiles. The initiating device was a Reynolds exploding bridgewire detonator (RP-83). In order to prevent acceptor-to-acceptor interactions, two steel barriers were set up next to each acceptor pallet on the lines of sight to the adjacent acceptor pallets, without interfering with the line of sight to the donor pallets. Steel witness plates, 1/2 in thick, were placed under the acceptors in the second and third tests to indicate the severity of reaction. High-speed cameras were set up 1,200 feet from the donor at 65 and 110° from north. After each test, most of the fragments and all of the projectiles were collected for evaluation.

FRAGPROP Analysis. An analysis of the test configuration was conducted using FRAGPROP. In previous analyses, Jacobs-Roslund constants for flat-tipped projectiles had been used as a worst case. In the present analysis, these were replaced with constants for hemispherical-tipped projectiles, which are considered more representative of the actual fragments produced by the M107 projectiles. The results of this analysis are summarized in Table 1. Probabilities of propagation of detonation and burning at stack-to-stack separations of 55, 39, and 28 feet are given.

Table 1. Results of FRAGPROP Analysis

Range	55	39	28
Detonation Probability	25%	50%	75%
Burning Probability	29%	55%	80%

Results and Discussion. In the first test, with the acceptor pallets placed 39 feet (skin to skin) from the donor (corresponding to a 50% predicted probability of detonation propagation), the east, south, and west acceptors did not react. Each of these three stacks was knocked over, and the pallets were broken apart. Most of the projectiles in the row facing the donor stack had fragment impact marks, and one projectile from the east acceptor pallet had a penetrating impact into the explosive, but no reaction ensued. The north acceptor pallet reacted violently. All of its projectiles exploded, but all of their base plates were recovered, as shown in Figure 3. The recovered fragments were generally larger than those produced by the (detonated) donor. These factors indicate that violent deflagration rather than detonation took place. Large fragments were thrown as far as 1,200 feet from the initial location of the stack. The explosions left a small crater. The possibility of lower order reactions had not been previously considered, and it was decided to place witness plates under the acceptors in subsequent tests to provide an indication of the order of reaction.

Figure 3. Large Fragments Recovered from North Acceptor in Test 1.

In the second test, in order to increase the probability of propagation, the acceptor pallets were placed closer to the donor (28 feet, corresponding to a 75% predicted probability of detonation propagation). In this case, the north and south acceptors detonated. The witness plate at the south acceptor is shown in Figure 4. The west acceptor did not react, and all eight projectiles were recovered nearby. The east acceptor reacted violently but did not detonate. Its witness plate showed that the middle two projectiles in the row facing the donor and the second projectile from the left in the back row reacted. The remaining projectiles were ejected to distances of 550, 800, 800, 980, and 1,200 feet from their initial location.

In the third test, the acceptor pallets were also placed 28 feet from the donor. One projectile in the north acceptor stack reacted violently, scattering the other seven projectiles around the range. These projectiles were thrown to 200, 360, 615, 630, and 900 feet, with two projectiles remaining within a 200-foot radius. The east acceptor pallet detonated producing a large crater, shown in Figure 5. The south acceptor pallet did not react but was blown over and broken apart. Two projectiles in the west acceptor reacted violently, throwing the other six projectiles out to distances of 220, 300, 340, 700, and 920 feet, with one projectile remaining within a 200-foot radius.

In the second and third tests, three of eight acceptors (37.5%) detonated at a distance corresponding to a predicted frequency of detonation propagation of 75%. Three of the remaining five acceptors (60%) reacted violently at a distance corresponding to a predicted frequency of burning propagation of 80%. The predicted frequencies of detonation and burning propagation are somewhat greater than those observed in the tests.

Figure 4. South Acceptor Witness Plate from Test 2 Showing Evidence of Detonation.

Figure 5. Crater from East Acceptor Detonation in Test 3.

Brief Review of FRAGGEN

FRAGGEN (Starkenberg, Dorsey, and Frey 1996) is a simple model for estimating the fragment output from any item that can be represented as a cylindrical charge with a fragmenting case. It does not account for fragment interactions with neighboring items. The distribution of fragment masses is given as a function of the average fragment mass by the Mott equation (Victor 1994). The average fragment mass may be related to the properties of the charge and casing, and the total fragment mass is equated to the casing mass. The velocity of the fragments is determined using the Gurney analysis for the assumed configuration and is the same for all fragments.

Fragment Characterization (Arena) Tests

Choice of Ammunition. The first objective of the series of arena tests was to provide fragmentation data for a thin-walled shaped-charge missile warhead for comparison to a FRAGGEN analysis. The AGM-114A Hellfire missile was chosen for availability. Its warhead has 14.1 lb of LX-14 in a thin aluminum case, and its motor has 20.5 lb of nondetonable propellant. It is classified 1.1E for storage and shipping. The first arena test was performed on a single Hellfire missile without its container. Since the missile is not generally stored in this configuration, another arena test with two simultaneously detonated missiles in their containers was performed. Finally, in order to address the issue of how to treat in situ detonation of weapons carrying submunitions, a test with a pair of 155-mm M864 ICM projectiles was attempted. Each projectile contains 72 submunitions, containing a total of 4.81 lb of Composition-A5 and 2.6 lb of base-burn HTPB-AP rocket propellant. The submunitions in the projectiles used in these tests were unfuzed.

Test Arrangement. The arena configuration for the Hellfire missile tests is illustrated in Figure 6. In the first test the Hellfire missile without its container was laid horizontally on a wooden stand with the centerline of the missile 4 feet above the ground. Bundles of Cellotex (4 feet wide × 8 feet high × 2 feet deep), numbered from 1 to 12 in a clockwise direction, were set at a distance of 30 feet from the center of the missile at azimuthal stations 10, 20, 30, 40, 50, 70, 80, 90, 110, 120, 140, and 150° from the nose of the missile. The front surfaces of the bundles were covered with thick aluminum foil to produce visible flashes for measurement of fragment impact times. Three propellant witness panels (designated A, B, and C) were set between some of the Cellotex bundles, at a slightly greater distance from the missile. These consisted of steel plates with on which six M203A1 metal canisters for 155-mm Howitzer were mounted. Each canister contains 30 lb of M31A1E1 stick propellant in a combustible cartridge case. They are classified 1.3C for storage and shipping. A 24-in-high plywood fence was set up at a distance of 16 feet from the missile to prevent ricochet hits on the witness panels. The Hellfire missile was detonated by firing a bare Viper shaped charge through the center of its warhead. Two high-speed cameras were placed 400 feet from the missile and recorded the tests at a speed of about 6,000 frames per second. The second test, with two Hellfires, was arranged similarly to the first test. The two missiles, in containers, were laid horizontally on a wooden stand, one above the other, with the centerline between them 4 feet above the ground. The ricochet fence was moved out 6 in and its height decreased to 20 in. The missiles were detonated simultaneously using two bare Viper shaped charges placed symmetrically, one above the top missile warhead and the other beneath the bottom missile warhead. The arena configuration for the M864 projectile test was similar and is illustrated in Figure 7.

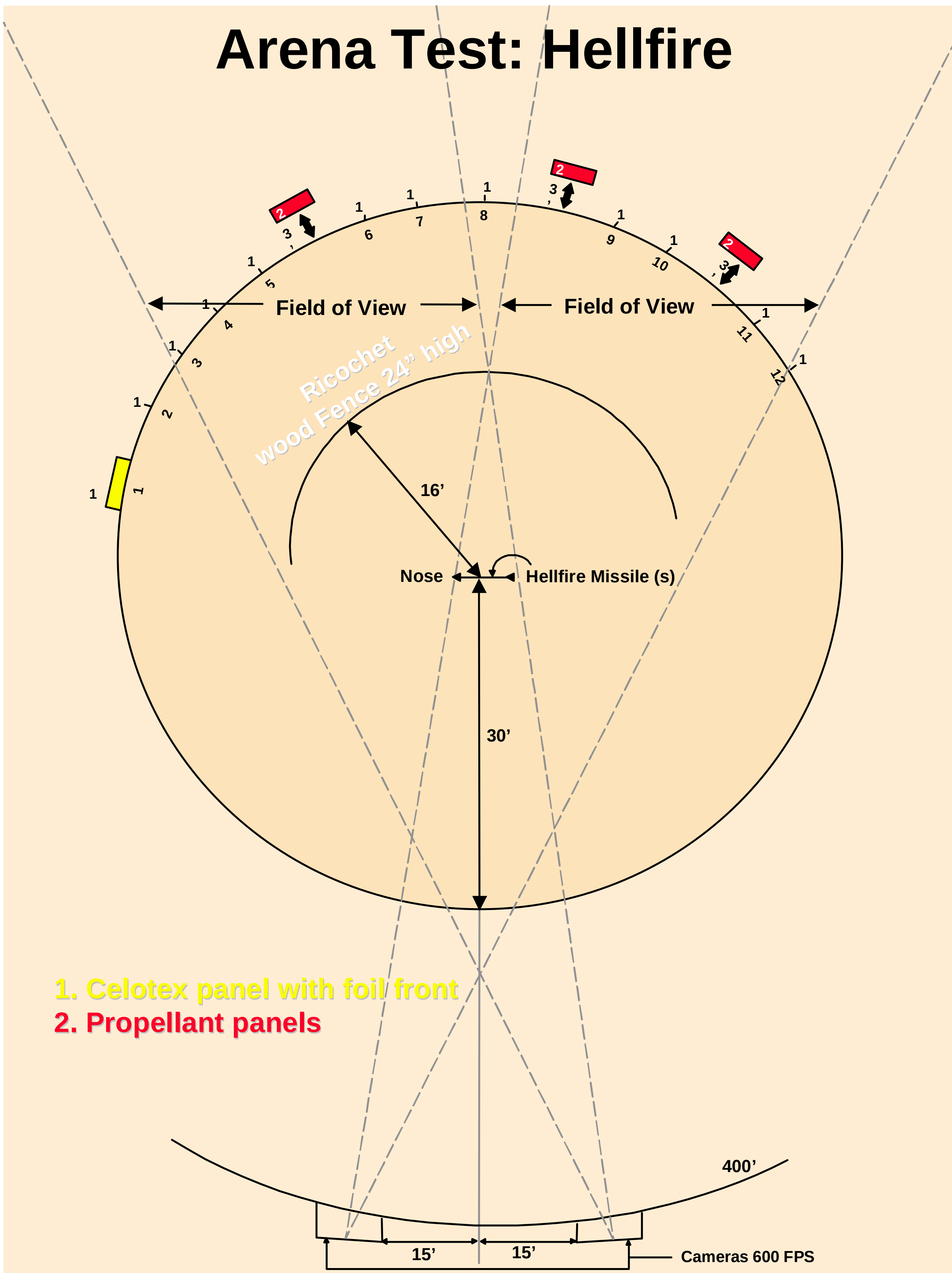


Figure 6. Schematic of Hellfire Missile Arena Test.

Two projectiles were positioned horizontally on a wooden stand with the centerline between the projectiles 4 feet above the ground. Only six Cellotex bundles were used, along with the three propellant panels, at a distance of 23 feet from the projectiles. These could be placed closer to the M864s because of their lower explosive weight. A 21-in-high ricochet fence was placed 13.5 feet from the projectiles. The projectiles were primed in their expelling charge cavities with Composition-C4. This was detonated with a Reynolds exploding bridgewire detonator (RP-83) through two 18-in lengths of detonating cord.

Results and Discussion. In the first arena test, the detonating warhead broke up the missile and ejected the motor 37 feet rearward. The motor did not react and remained intact with no rocket propellant exposed. None of the witness propellant canisters showed any type of reaction and there were no penetrating impacts to any of them. The high-speed films were examined and found to have 6,170 frames per second. The only position not obscured by the fireball from the warhead detonation was at 150°, where flashes on the aluminum foil from fragment impacts were noted on the film and velocities were determined to range from 320 to 1,568 m/s. The fragments collected from the Cellotex bundles were weighed and identified as aluminum, copper, or steel. Distributions with azimuthal zone of the number of fragments and their total and average masses are shown in Figure 8. The aluminum fragments are generally small and distributed throughout the arena. Most of them are primary fragments from the warhead casing, although several larger aluminum pieces were retrieved from the Cellotex bundle at 150°. Fragments larger than 3 g were found in only a few of the azimuthal zones. The copper fragments are larger and are concentrated in the 30 to 50° azimuthal range. The steel fragments are also larger and distributed mostly toward the forward and aft azimuthal zones. FRAGGEN predictions for an idealized representation of the Hellfire warhead were made. The assumption of a cylindrical LX-14 charge, 246 mm in length × 175 mm in diameter, with a 1.27-mm-thick aluminum case, gives a total of 1,878 fragments with an average mass of 0.247 g and a velocity of 3,896 m/s. Assuming a uniform distribution about the missile axis, only about 64 of these fragments would be expected to strike the Cellotex bundles. Actually, 238 aluminum fragments with an average mass of 0.85 g were recovered. These do not all come from the warhead casing. The larger fragments are probably secondary fragments. However, even if attention is restricted to fragments smaller than 1 g, there are still 202 fragments with an average mass of 0.22 g. Even though this average mass is close to the predicted value, there are still too many fragments. The Mott equation has been used to predict the distribution of fragment masses. The predictions are compared with the arena test data in Figure 9. The agreement is quite good to about 0.2 g, but, thereafter, the actual fragment distribution drops off more rapidly than the predicted distribution. The predicted fragment velocity is much higher than any measured velocity.

In the second arena test, the simultaneous detonation of the two missile warheads produced a large blast wave and heavy fragmentation. There was an immediate reaction in a propellant canister in witness panel C, spreading burning propellant over a 50-foot radius. After approximately five minutes, the Cellotex bundles ignited and started burning. Upon reentering the range, all of the Cellotex was found to have burned. All of the propellant canisters had burned out, and some were thrown as far as 400 feet from their initial locations. Three canisters in witness panel C had penetrating fragment holes where the fire may have started. Large amounts of unburned propellant were scattered around the entire arena area and scorch marks on the ground indicated that much propellant had been ignited and burned after being ejected from the canisters. One of the missile

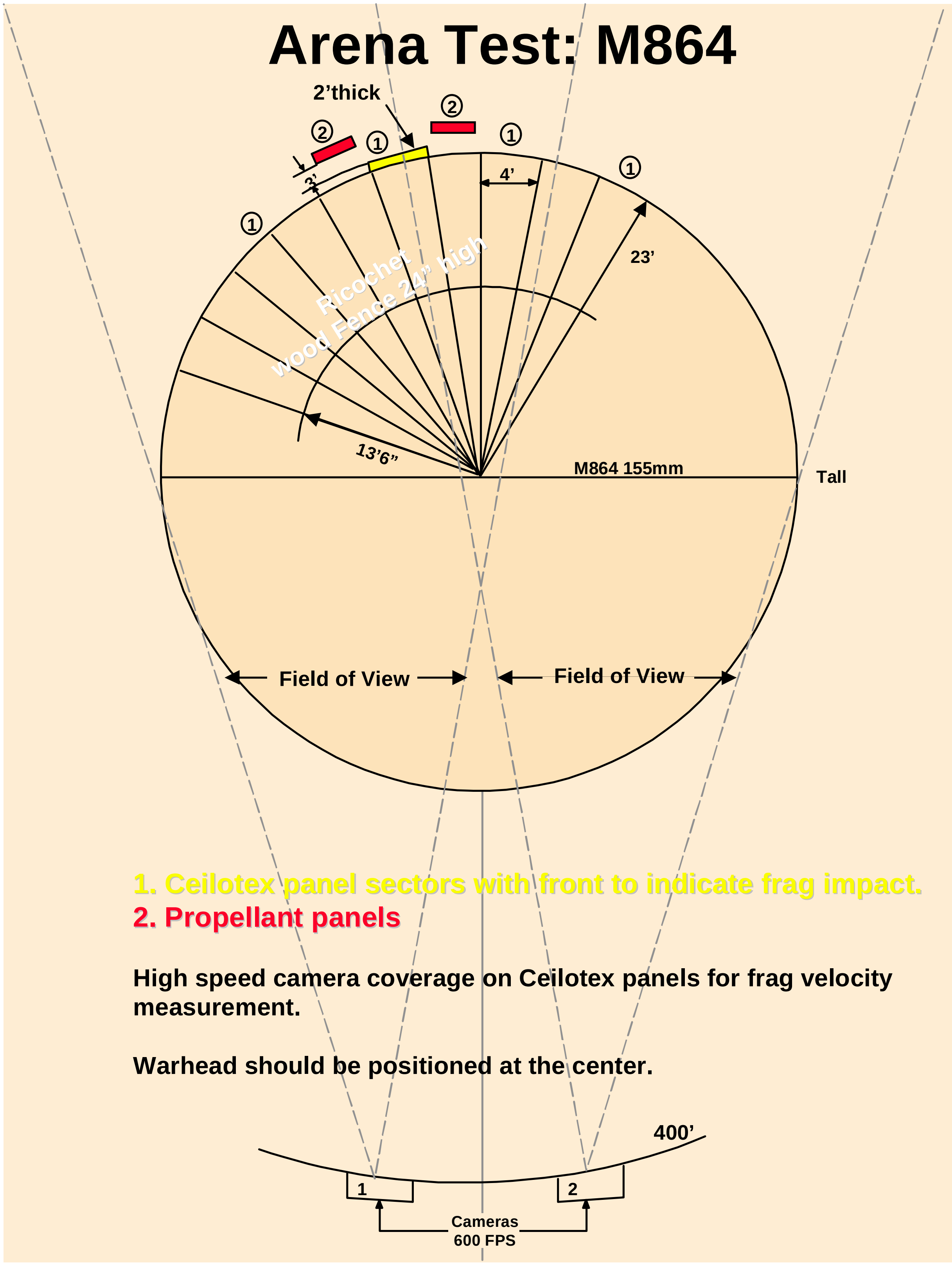


Figure 7. Schematic of M864 Arena Test.

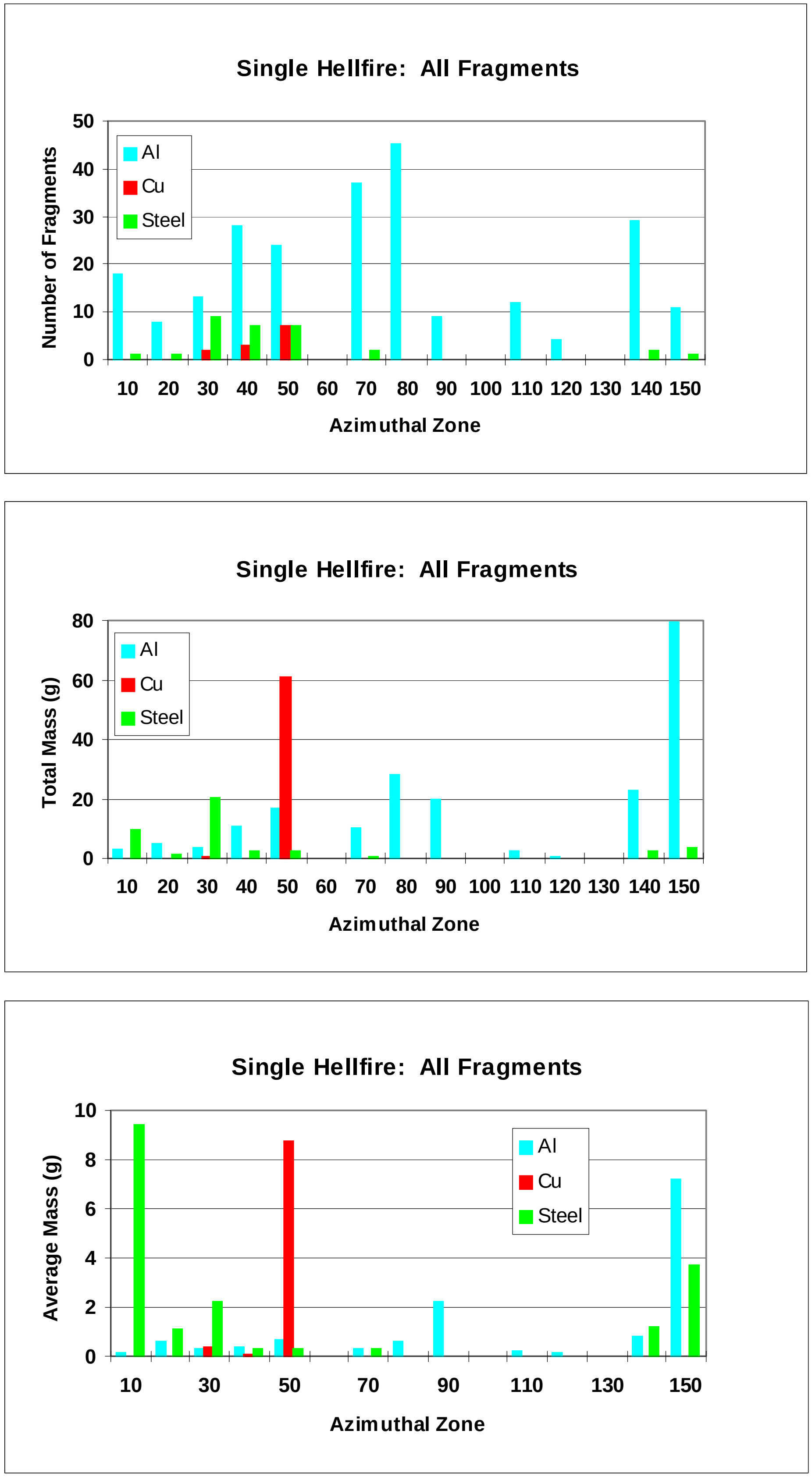


Figure 8. Distributions of the Number of Fragments, the Total Fragment Mass, and the Average Fragment Mass with Azimuth—Single Hellfire.

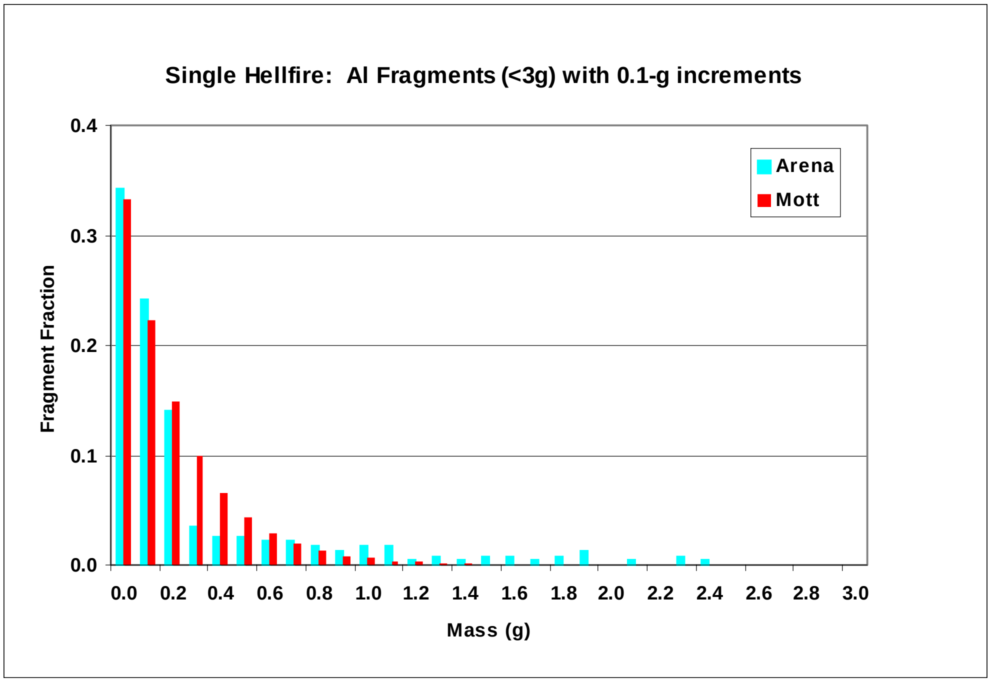
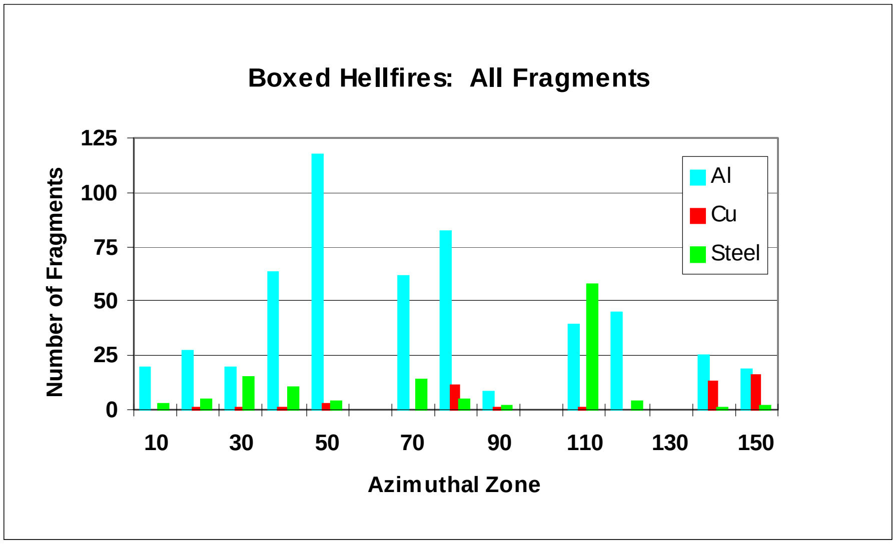
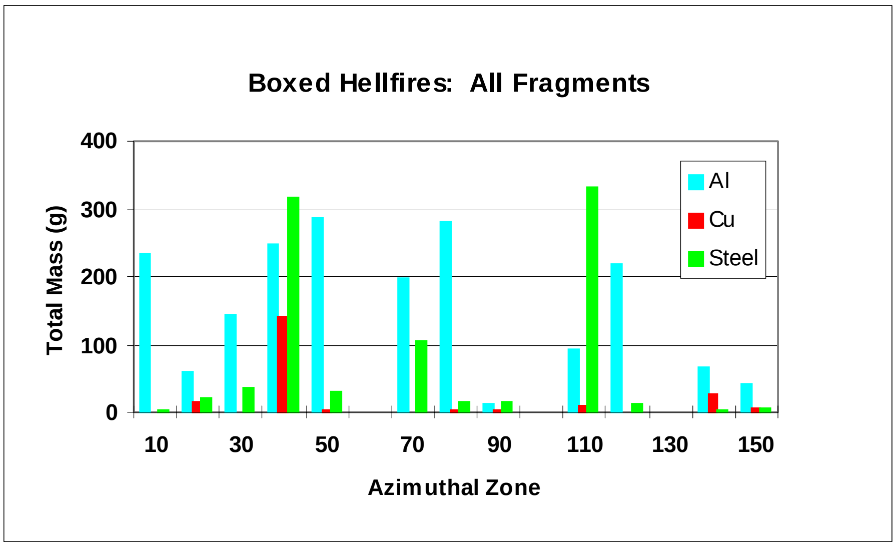


Figure 9. Distribution of Fragment Mass—Single Hellfire.

motors had been ejected intact 31 feet to the rear. The other ignited and was observed to fly upward approximately 300 feet, landing 600 feet from its initial position along an azimuth of 270°. Because of the large fireball from the two simultaneous missile detonations, flashes on the aluminum foil from fragment impacts could not be seen in the film and velocities could not be estimated. The fragments collected from the Cellotex ashes included missile and container parts. They were weighed and identified as aluminum, copper, or steel. Distributions with azimuthal zone of the number of fragments and their total and average masses are shown in Figure 10. The aluminum fragments include primary fragments from the warhead casing and secondary fragments from the container. There is a greater percentage of large (>3 gm) fragments than produced by the single Hellfire detonation, and both large and small fragments are distributed throughout the arena. Large copper fragments were recovered from the 40° azimuthal zone and numerous small copper fragments were found at 80, 140, and 150°. Large steel fragments were also recovered from the 40° azimuthal zone, and smaller steel fragments were distributed throughout the arena, with numerous small fragments at 110°. The distribution of fragment masses is compared to that from the single hellfire test in Figure 11. In the boxed Hellfire test, the smallest fragments appear more infrequently, while somewhat larger fragments appear more frequently. The smallest fragments may have been scrubbed by the container.

In the third arena test, the two M864 projectiles appeared to detonate simultaneously, but it was noted that several large fragments were launched. There was an immediate reaction from the propellant canisters on witness panel. Canister lids were ejected, and burning propellant was blown around. At about 30 seconds after the initial blast, three detonations were heard and are assumed to be submunitions cooking off in the propellant fires. Propellant from witness panel C continued to burn over the entire arena for about two minutes igniting many of the Cellotex bundles. The projectile body fragments were very large (about 3 in × 12 in), indicating a low-order response in the





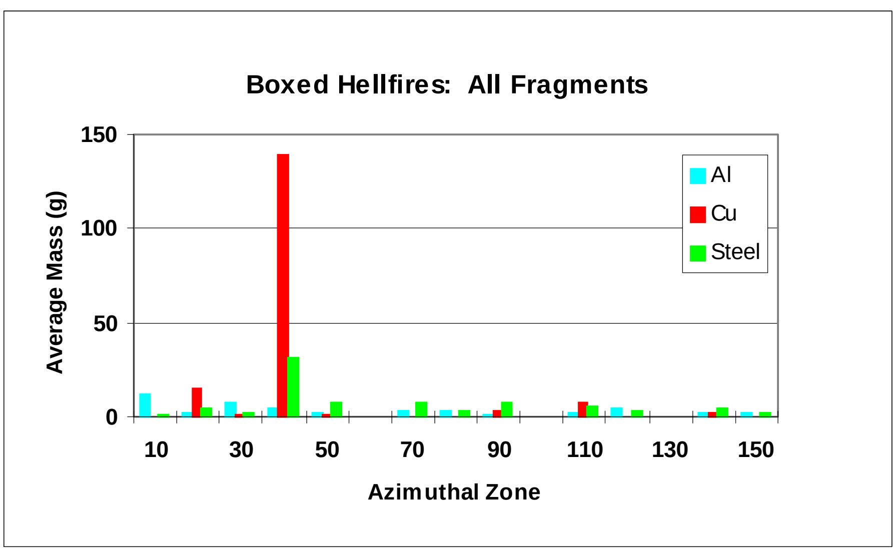


Figure 10. Distributions of the Number of Fragments, the Total Fragment Mass, and the Average Fragment Mass with Azimuth—Boxed Hellfires.

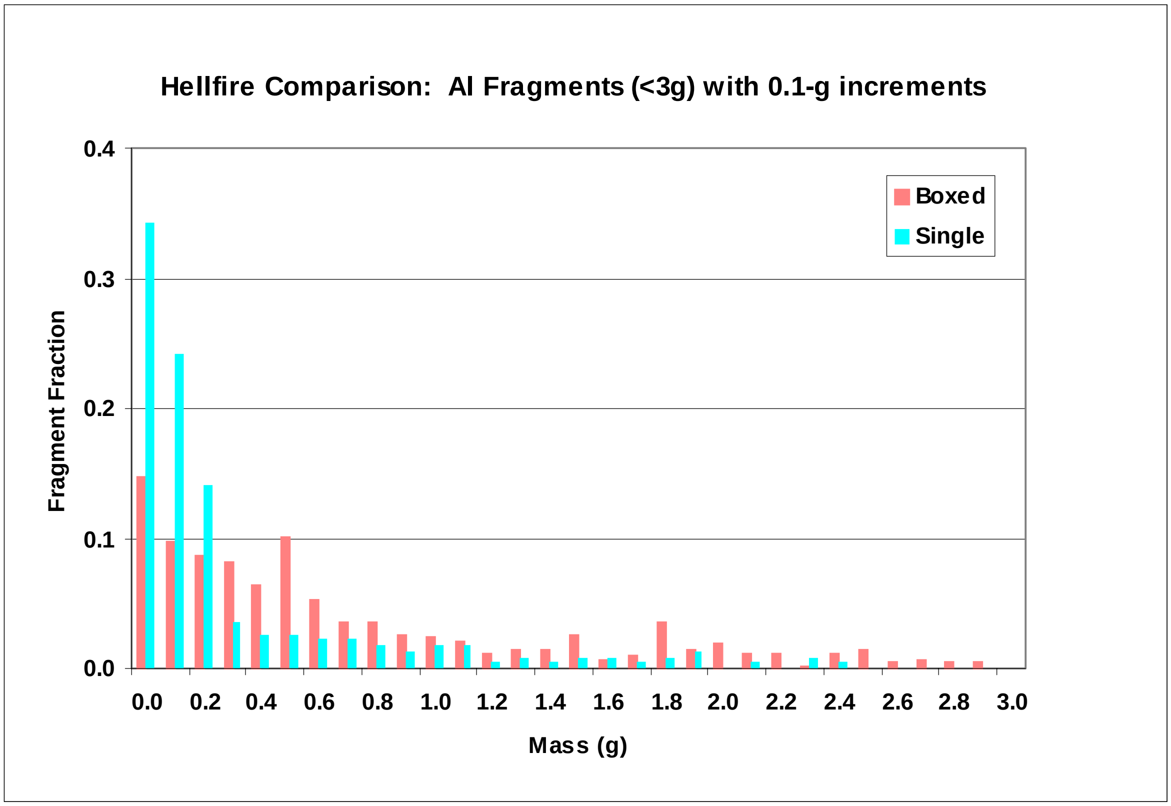


Figure 11. Distribution of Fragment Mass—Comparison of Single and Boxed Hellfires.

projectiles. Twelve of the 144 submunitions were recovered nearly intact around the arena area. Only three propellant canisters remained in the arena area. The remaining 15 canisters were thrown clear of the arena. Of these, one flew to 250 feet, and the rest were scattered within a 200-foot radius. No analysis was conducted.

Summary and Conclusions

In order to benchmark predictions from FRAGPROP, propagation tests using 155-mm M107 ammunition were conducted. The predicted frequencies of detonation and burning propagation are somewhat greater than those observed in the tests. While the results do not provide sufficient data to validate the FRAGPROP predictions with a high level of confidence, they indicate that they are reasonable representations of the actual responses of these munitions.

In order to benchmark predictions of fragmentation from a missile warhead generated by FRAGGEN, an arena test on a single Hellfire missile was performed. Aluminum fragments, in addition to those produced by the warhead, were recovered and analyzed. The analysis indicates that the predicted distribution is accurate for the smallest fragments, which comprise most of the total number. Measured fragment velocities were much lower than the Gurney predictions employed by FRAGGEN, and the fragments failed to ignite any of the witness propellant canisters.

Because the configuration used in the single Hellfire test does not represent the actual storage arrangement and in order to determine the effects of multiple simultaneous detonations and the presence of external packaging, an arena test on two Hellfire missiles in their containers was conducted. Under these conditions, the Hellfires pose a hazard to nearby propellant canisters as evidenced by the reactions observed. Comparison of the fragment mass distributions produced in the two tests indicates depopulation of the smaller fragment sizes in the second test. This renders the FRAGGEN predictions inaccurate. The fragments produced in this test started burning reactions in the witness propellant canisters.

A final arena test with two 155-mm M864 ICM projectiles containing submunitions, conducted in an attempt to develop fragmentation data for this configuration was not successful.

Acknowledgments

The authors are grateful to Carl Halsey and his crew at China Lake for completion of the tests and to the Defense Ammunitions Logistics Activity for funding this effort.

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